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Very High Energy $\gamma-$ ray Emission from Crab and Geminga Pulsars

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Abstract. The main inference from the experiments of the '80s that the time-averaged energy spectra of pulsars had to steepen in the GeV-TeV energy region has been reinforced in the '90s from experiments with higher sensitivities. However, results from several experiments from the past and the more sensitive experiments at present can be reconciled by invoking a possibly different component arising in the TeV region. The results of the preliminary analysis of the data being collected with the PACT array will be presented.

1 Introduction

Almost all the VHE $\gamma-$ ray groups looking for VHE $\gamma-$ ray emission from pulsars in the '70s did find some signals from the Crab pulsar, but the results could not be repeated. While there were several possible reasons for non-reproducibility of the results , it was becoming clear from later experiments in '80s that time averaged pulsar spectra have to steepen at the energies 500 to 1000 GeV. As we will see below, these tentative conclusions from that era have been borne out in general by the more recent and sensitive VHE $\gamma-$ ray experiments, with both imaging and non-imaging techniques. Pulsar studies have become more interesting for the VHE gamma ray astronomer since the EGRET results which detected seven $\gamma-$ ray pulsars [Thomson (2000)]. At > 1 GeV energies, the light curves change with the dominance of either the main or the inter pulse. Further the spectra show dominant power at energies of ≤ 1 GeV with a falloff at higher energies. All these features indicate changes in characteristics at higher energies. Thus, the VHE $\gamma-$ ray experiments have the interesting task of finding the cut-off energies for the emission mechanism acting at the MeV-GeV energy region in the environs of the pulsars. The Outer Gap(OG) models for pulsar emissions predict an inverse Compton component due to gap accelerated particles with a peak around 1 TeV. While there are variations in the OG models, all models predict a TeV

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emission component. Thus, while the emission process giving rise to MeV-GeV gamma rays could peter out at sub- TeV energies, it is important to detect other processes in pulsars which could give rise to GeV-TeV $\gamma-$ rays. While the recent trend in the field has been to lower the threshold energies, it is interesting that one has really to look at the higher energy part of the data to detect this emission. Preliminary results from a new experiment which has started out at Pachmarhi will be specially looked at for evidence for these higher energy emissions. Recent reviews on VHE gamma ray emission from pulsars can be found in Fegan [Fegan (1996)] and Kifune [Kifune (1996)].

2 Earlier Results on Crab and Geminga Pulsars

While there have been many observations in the 1970s with and without absolute phase information, we will restrict ourselves to the results in the 80s which in general had absolute phase information. The Durham group, working at the Dugway site in USA, detected a 4.3σ signal at the main pulse phase position from 103 hours of observation at an energy threshold of 1 TeV. The flux was found to be 5×10^{-12} $sec^{-1}\ cm^{-2}$. It should be noted that the detected flux is quite small, about 3 per hour. With arrival direction estimation, they also showed that the signal falls off away from the pulsar direction. The Tata group, earlier at Ooty and later at Pachmarhi, had many hours of observation on the pulsar and detected transients but no time-averaged signal. As a representative of the Tata observations, one can use the Ooty results of 3 years (a total of 105 hours of observation), all with absolute phase, which did not show a signal at the main peak and where an upper limit of $4.6 \times 10^{-12}sec^{-1}cm^{-2}$ for Energy > 800 GeV was derived for the time averaged emission.[Vishwanath (1987)] The Asgat experiment, with 50 hours of exposure, derived an upper limit of 2.2×10^{-12} $sec^{-1}\ cm^{-2}$ at >600 GeV[Goret (1993)]. Recently, a thorough search for pulsed emission has been done with the Whipple imaging telescope.[Burdett (1999)] Using the data col-

lected between 1995 and 1997, for an exposure of about 73 hours, they give an upper limit for pulsed emission to be $4.8 \times 10^{-12} sec^{-1} cm^{-2}$ and $1.2 \times 10^{-12} sec^{-1} cm^{-2}$ above > 250 and 1000 GeV respectivley. HEGRA experiment has also given only upper limits for emission of VHE $\gamma-$ rays from Crab abd Geminga pulsars. [Aharonian (1999)] The CELESTE experiment and the STACEE experiments, both with solar arrays, also do not see evidence for pulsed emission in their respective energy regions.

After the mystery that Geminga had created in the '80s was resolved by the EGRET experiment in the '90s, two groups [Bowden (1993)],[Vishwanath (1993)] found modest pulsar signatures in their archival data with VHE $\gamma-$ ray peaks coinciding with the peaks in the low energy data. The flux reported by the Ooty group(with simultaneous observation at 2 sites for a total of 28 hours) at energy thresholds of 0.8 and 1.7 TeV was $2.1 \times 10^{-11} sec^{-1} cm^{-2}$ and $0.44 \times 10^{-11} sec^{-1} cm^{-2}$ respectively. Later, in the '90s, an upper limit for pulsed emission from Geminga was given by the Whipple imaging telescope.[Akerlof (1993)]

During 1992-1994, the Tata group working at Pachmarhi ran an interim array for testing some of the hypothesis concerning Lateral Distribution(LD) (discussed below) of VHE $\gamma-$ rays. 8 banks of mirrors, each of total area $2.5m^2$ were deployed in a 80m $\times$ 100m area. The exposures for Crab and Geminga were 80 and 49 hours respectively [Vishwanath (1997)]. It was shown that the events at phases at which GeV emission was found(Main pulse region for Crab and around 0.6 for Geminga) displayed the same features as expected from gamma ray events. The mean Cerenkov light (measured in ADC units) per event was also higher at these phases, an indication of the gamma ray admixture. The number of events at the Main Phase region for the Crab was about 3.5 per hour.

3   The new results from PACT

A totally new set up PACT has been commissioned recently at Pachmarhi with 25 telescopes, each with 7 mirrors , having a total area of $105m^2$ of mirrors [Bhat (2000)] for using both the LD aspects and the arrival direction information for the increase of sensitivity. A total of 45 hours of data and 20 hours of data on Crab and Geminga pulsars were taken respectively. While the Crab data ranged from runs in Nov 1999 to Nov 2000, all the Geminga data was taken in Dec 2000. While the ephemeris for Crab was taken from the data provided by the Jodrell Bank, the latest parametrization of the EGRET group for the pulsar period was used for Geminga. Standard algorithms were used to get the phase for each event. Fig 1(a) shows the Crab pulsar phasograms without any cut and with the cuts. It can be seen that the phasogram without any cut does not show any significant emission at any phase. Therefore, an upper limit to the time averaged emission is derived above >900 GeV as $2 \times 10^{-12} sec^{-1} cm^{-2}$ This upper limit is similar to those set by most experiments (Results on Geminga will be presented later in the confer-

ence).

Many simulations, including the recent extensive calculations by Chitnis and Bhat [Chitnis (1999)] have shown that the gamma ray lateral distribution (LD) is very different from that of protons in having an almost constant density till about 120 meters where it becomes higher resulting in the so called hump region (a result of the focusing property of Cerenkov radiation) for the next 20 meters. The fall off from the hump region is similar to the monotonic decrease for the proton showers from the core. The Monte Carlo simulations with these inputs for the PACT array showed that a gamma ray event would have at large values of total Cerenkov pulse height since a typical gamma ray would deposit much more Cerenkov light than a typical cosmic ray. Further, it was seen that β, a LD parameter which is a measure of how large the detector with the maximum pulse height would be compared to the rest of the detectors, would be useful for distinguishing between proton and gamma ray showers. The details are discussed in the conference papers of the PACT experiment.[Vishwanath (2001)]

The experiment is capable of good angular resolution. Cuts were applied on the space angle difference between the event and the pulsar direction. Further, a cut was imposed on the number of mirrors hit and the β parameter both of which place the events at higher energies. The peak seen at the Main Pulse phase in the lower half of Fig. 1 is a 4 σ signal. Fig 2 shows the rate per hour of the events in the Main Pulse region for the 3 sub periods (1999 Nov, 2000 Jan, 2000 October and 2000 November) of the data taking. Within errors, the rate is same for the 3 data periods. The mean rate is 3.4 $\pm$ 1.2 per hour which compares well with the detected rate with the interim array with similar cuts discussed above.

4   Discussions

It is certain that most of the pulsar energy spectra have to steepen in the energy range of the atmospheric Cerenkov experiments. The precise energy region of the steepening will be clear when some of the lower energy threshold experiments become fully functional. By locating the cut-off energy, the experiments can help distinguish between the contending models for gamma ray emission by pulsars. Polar Cap models predict steep spectral cut-offs due to magnetic pair production attenuation and essentially no detectable emission above about 50 GeV. The spectral cut-off predicted in OG models is more gradual.

Some comments have to be made about the results from the earlier generation experiments. Lacking detailed Monte Carlo calculations which are regular features of the present day experiments, the energy thresholds and collection area estimates would have been less precise. However, the calculations in getting the pulsar phase for the event had been well known. Further, when at least two experiments see the same effect at the same phase, the credibility of the overall effect should be quite high. Some remarks are also in order about the non-reproducibility which plagued experiments
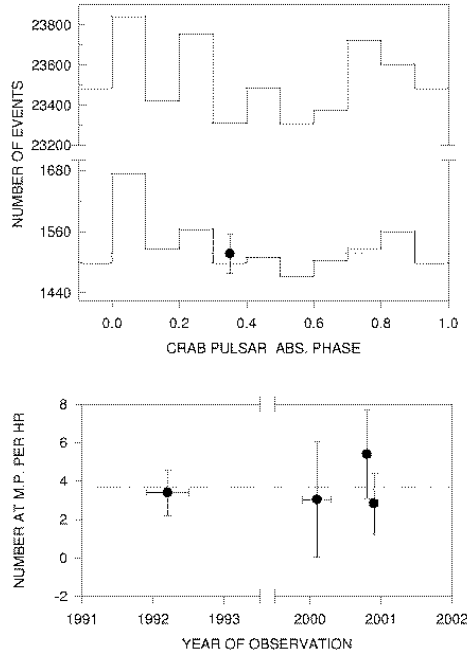
Fig. 1. (a)The phasogram of events from Crab pulsar during 1999-2000. The top part is the phasogram of all events without any cuts. The bottom part is the result of several cuts (see text). (b) The rate of detected events in the Main Pulse region. The data are from the 1992 Interim array and the recent PACT experiment

in the early days when the energy thresholds of experiments were varying with constant attempts to lower the threshold. If a new component does surface at > 1 TeV energies, it is not surprising that there were conflicting results depending on the energy threshold of the experiment.

It is seen that the recent results from the Pachmarhi experiment do indicate a finite number of events from the Crab Pulsar. While the cuts need to be understood properly before an actual flux could be given, it would be obviously greater than the detected flux which is at the level of $7 \times 10^{-13} sec^{-1} cm^{-2}$. It should also be noted that the cuts for the data place the events detected at energies > 1.5 to 2 TeV, much greater than the actual energy threshold of the experiment. The fact that similar flux was seen from the interim array is also interesting. Thus, it is possible that the earlier results from Durham as well as the new preliminary results from Pachmarhi do point to a new pulsar component at higher energies.

Long exposures are very necessary to detect such flux levels. Detected flux from the Crab pulsar is 2-3 per hour in the experiments of Dowthwaite et al and the recent results from the Pachmarhi experiment. This has to be compared to the flux levels of 2-3 per minute from the whole nebula. If there is a finite flux from the Crab pulsar at TeV ener-

gies, it should show up as a mild bump in the overall energy spectrum from Crab. If the nebular emission at few hundred GeVs is solely due to inverse Compton scattering process, a new process at TeV energies should add to the nebular flux. One should however keep in mind the very low flux from pulsar and only experiments with good energy resolution will be able to opine on this issue.

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